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SUSPENDED SOLIDS WASHING OVERVIEW

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ABSTRACT

Suspended solids are washed from pulp primarily to improve brightness and drainage, alter the mechanical properties of the final sheet, and remove fillers and dispersed coatings. Suspended solids washing is discussed relative to retention and filtration theory (particle capture via surface attractive forces, and sieving), because it shares more with these processes than with dissolved solids washing.

Particles which are candidates for removal by suspended solids washing range in size from less than 0.1 μm to several hundred μm. Surface attractive forces can cause attachment of a particle smaller than a few μm to fiber surfaces, thus reducing washing effectiveness. Changes in electrophoretic mobility, due to charge neutralization, or due to pH changes, can dramatically alter particle capture on fiber surfaces. Surfactants can be used to isolate hydrophobic particles, effectively preventing fiber surface capture. Particles larger than a few μm are poorly retained via fiber surface capture, unless retention aids are present. Sieving capture increases with increasing particle size and mat density, and when less coarse fibers are present in the fiber mat. Particles larger than about 50 μm are removed with poor efficiency.

If fiber surface capture is suppressed with appropriate washing chemistry, washing effectiveness can be improved, especially for larger particles, by using hydraulic shear, or turbulence, to reduce the effectiveness of capture by sieving. Since higher shear levels also tend to increase the loss of fiber solids, the various washer operating parameters must be chosen carefully, such that sufficient washing is achieved, with minimal loss of usable fiber solids.

INTRODUCTION

Suspended solids must be washed from pulp for a variety of reasons, especially during the recycling of paper. Almost all of the mechanical properties of the sheet, and many of the paper machine operating parameters, are dramatically altered by the presence of fines, fillers, and dispersed coatings. For example, filler and coating pigments interfere with fiber to fiber bonding, which reduces the mechanical strength properties of the sheet. Filler, dispersed coatings, and fiber fines also reduce drainage on the paper machine. Small ink particles reduce the brightness of the pulp, while larger ink particles (greater than 50-60 μm) leave visible ink specks in the finished sheet. Even small quantities of dispersed sticky particles, and colloidal pitch particles have been observed to agglomerate into larger particles, or deposit onto wetted surfaces at the paper machine, where they cause a variety of visual defects, and runnability problems.[1-5]

The often suggested practice of using the paper machine as a washer, by discharging a large quantity of filler, ink, and fines-laden water to the clarifier, is cost prohibitive, due to the cost of suspended solids losses and water treatment. It is also ineffective, due to the chemistry at the wet end, which tends to promote retention of suspended solids on the fiber surfaces. As mills seek to close up their water systems, and as retention aid chemistry improves, this option becomes even less attractive. In the future, mills with totally closed or nearly closed water systems may find it necessary to wash out precipitated non-process elements, and very small adhesive particles, as a means of purging them from the system.

The technical literature contains very little information concerning the theoretical aspects of suspended solids washing. In most cases, it is assumed that the suspended solids follow the water split in a washer, much like the dissolved solids theoretically do. This is not strictly true for dissolved solids, which may be partially sorbed, and substantially resistant to removal by washing. In addition, it is well known that time, elevated temperature, and concentration gradients are helpful for dissolved solids washing, because these assist diffusion of dissolved solids from the fiber surfaces, interstitial spaces, and cell walls.[6] These factors are generally unimportant for suspended solids washing, except for temperature, to the extent that it affects the viscosity of the fluid.

On the other hand, suspended solids removal may deviate from the water split because particles are caught in surface irregularities of the fibers, mechanically entrapped by fiber intersections, or held to the surface of fibers by various surface attraction forces. These mechanisms, while well known in filtration and retention theory, are not found in dissolved solids washing theory. For these reasons, washing

is discussed here as an extension of filtration and retention theory and practice, rather than as an extension of dissolved solids washing theory.

SUSPENDED SOLIDS CHARACTERIZATION

Size, Shape, and Surface Area

A wide range of suspended solids may be found in papermaking slurries, particularly those containing recycled papermaking fibers. These suspended solids include fibrous and non-fibrous particles, organic and inorganic particles, relatively large and small particles, and a variety of particle shapes. The suspended solids most often encountered are characterized in Table 1.[7-10]

The dimensions listed in Table 1 for the mineral substances, typically fillers or components of coatings, are their dimensions as they were initially received at the mill. In some cases, coatings do not break down completely, such that coating flakes which are significantly larger than the basic particle size, and quite different from the basic particle characteristic shape, may be seen.

The chemical environment, and mechanical action during repulping can also affect ink particle size and shape. The shapes listed for the various inks are as typically found in repulped printed paper, because these particles generally have been characterized in the form and size in which they appear after repulping.

The significance of suspended solids density is due to the influence of density on particle collision probability. In general, particles with densities much different than that of the suspending fluid are more likely to cross fluid streamlines, which increases the probability of collision with, and attachment to, fibers.

Table 1: Suspended solids characterization.[7-10]

Suspended Solids Particle	Nominal size (μm)	Shape	Density (g/cm^3)
Fibers, hardwood	1000	fiber	1.5*
Fibers, softwood	2-4000	fiber	1.5*
Fiber fines	<200	fibrils, flakes, cubes	1.5*
Coating grade clay	<2	plate-like	2.58
Filler grade clay	0.5-10	plate-like	2.58
TiO_2	0.15-10	sphere	3.9-4.2
Calcium Carbonate	0.5-3	irregular/ near spherical	2.7-2.85
Talc	0.5-5	plate-like	2.7
Toner flakes	10-500	flake, potato-shaped	1.1-1.8
Offset ink	2-100	spherical	1.5-2.0
Flexographic ink	<0.3	spherical	1.5-2.0
Coating flakes	20-500	spherical to flake-like	varies; usually >2.0
Precipitated non-process elements	?	generally spherical?	varies, usually >2.0

* Dry cell wall material only; effective density of swollen fiber varies.

FILTRATION, THICKENING, AND RETENTION THEORIES

Fiber Mat Filtration vs. Thickening

In his classic textbook, Parker[11] identifies two major mechanisms for dewatering on the paper machine: thickening, and filtration. Filtration occurs when the slurry is at such a low concentration that the fibers and other suspended components are free to move independently of each other. The result is a slurry of constant consistency, over a fiber mat of increasing thickness, as the filtration progresses. Filtration tends to form a fiber mat in which the fibers are overwhelmingly in the plane of the sheet, as if formed in infinitely thin layers. Filtration dewatering is also characterized by a sheet which is relatively consistent; the slurry tends to flow preferentially through the larger pores, where the resistance to flow is lowest, such that fibers tend to preferentially fill in the thin spots.

Thickening occurs when the fibers and other suspended solids are somewhat immobilized in a network, such that they do not

behave completely independently during dewatering. This can occur after the network is initially dewatered via filtration, or, from the onset of dewatering if the initial consistency is relatively high, or if the fibers are very long. There is no sharp boundary between the growing fiber mat and the slurry during thickening, because water is being removed from all areas at once. Thickening tends to form a sheet with some fibers oriented out of plane, or even perpendicular to the plane of the mat, a structure which is sometimes called "felted." Since the fibers are in the form of a network, the sheet may appear more flocked.

Retention of Small Particles in Fiber Mats

The overall mechanisms of suspended solids capture in a pre-formed fiber mat, as proposed by Raistrick,[12] are illustrated in Figure 1. Mat surface capture occurs when virtually all pores leading into the fiber mat are smaller than the particles, leading to an accumulation of particles only at or very near the surface of the mat which faces the direction of flow.

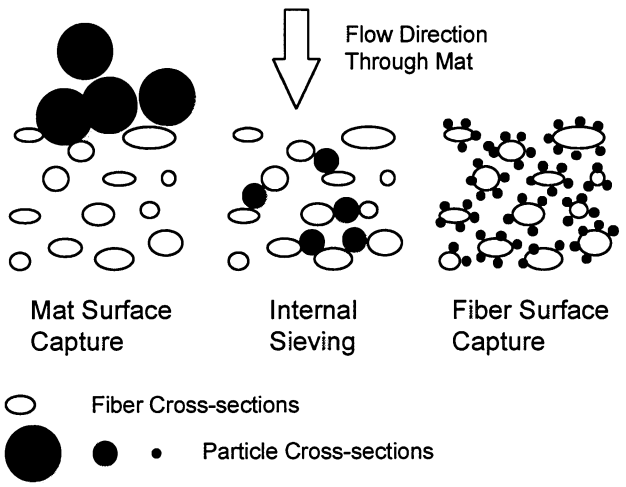

Figure 1: Particle capture mechanisms; left, mat surface capture; center, internal sieving; right, fiber surface capture (after Raistrick[12]).

Capture by internal sieving occurs when some internal passageways cannot pass the average particle size, such that particles are strained out in passageways throughout the depth of the mat. Both mat surface capture and internal sieving capture are mechanical in nature; they can occur only when the fibers are close together, relative to the particle dimensions. When the mat porosity is very high, there are very few locations where the fibers are within one particle diameter of each other, and hence there is little potential for retention by sieving, especially for very small particles. As the mat is compressed, and the fibers move closer together, retention by sieving must increase dramatically, approaching 100% when the average distance between fibers is much smaller than the average particle diameter. At that point, retention by sieving on the upstream side of the mat face mimics filtration through a filtercake, rather than media filtration.

Literature sources suggest that only 5% or so of the retention of fillers in normal papermaking takes place by sieving,[13] perhaps because the great majority of the water and suspended solids are removed from the sheet by the time the mat is densified to the extent that sieving can occur.

Fiber surface capture typically occurs when particles which are much smaller than mat pore diameter collide with the fibers, and are retained by electrokinetic and van der Waals forces. This mechanism is well established as the dominant mechanism for retention of filler in fibrous webs during papermaking,[14-17] and also in deep bed filtration,[18-19] commonly used in water treatment plants. A wealth of information is available in the literature, although the vast majority of this information characterizes particle collection under conditions of chemistry which are conducive to retention of particles by electrokinetic and van der Waals forces. These conditions are generally not favorable for efficient removal of suspended solids particles via washing, and certainly are not typical of the chemistry conditions preferred for effective washing in deinking applications.

Hyperwashing consists of washing at high dilution and modest shear conditions, until no further material can be washed out. It is commonly observed that as much as 0.4-1.5% of the fiber weight may be present as ash, even after hyperwashing, and regardless of the chemistry conditions, for deinking grades of recovered fibers.[20,21] This residual ash is thought to result from minerals which are incorporated into the fiber wall from the soil as the plant fiber grows, sorbed sodium or calcium, and filler and coating mineral particles which have become lodged in areas of poor accessibility, such as within deep surface fissures, and the fiber lumen. This very small amount of material is virtually a part of the fiber, and is not subject to removal by washing. Since this material is strongly bound to the fiber, not captured during the washing process, it has been ignored for the remainder of this discussion.

Mechanisms for Particle-Fiber Collisions

Both fiber surface capture and sieving are affected by mechanisms which control contact between the particles and the fibers. These include interception, inertia, diffusion, sedimentation, and hydrodynamic action.[19] These mechanisms are illustrated in Figure 2.

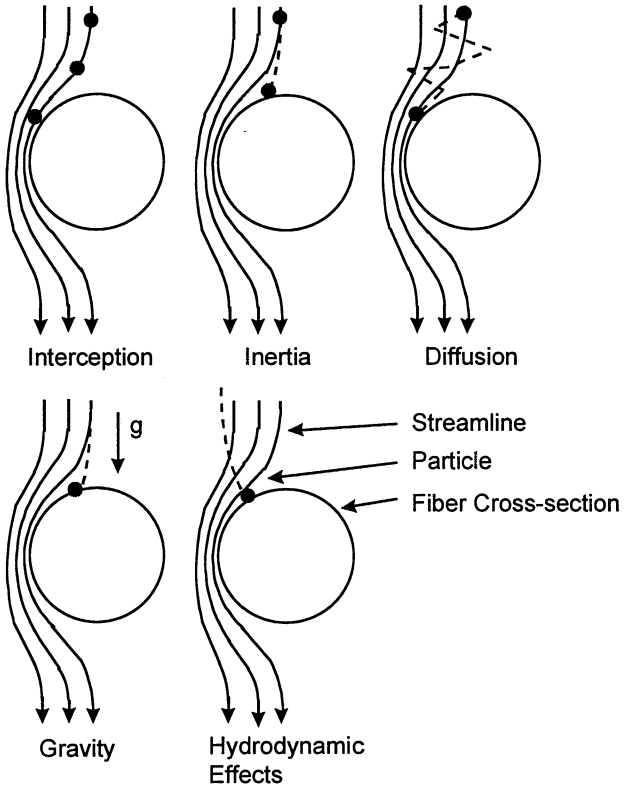

Figure 2: Mechanisms for particle-fiber collisions.

A particle which has the same specific gravity as the suspending fluid will follow the fluid streamlines around a fiber. If a streamline containing the centerline of a particle passes a fiber within half the diameter of the particle, the particle will collide with the fiber. The probability of collision of a suspended solids particle with the media during deep bed filtration has been found to be proportional to the diameter ratio of the particle to the media, as shown in Equation 1:[19]

$$P\alpha\frac{d_{particle}}{d_{media}} \qquad \text{(Equation 1)}$$

Equation 1 assumes that the media diameter characterizes the pores of the media bed, a reasonable assumption for beds of incompressible granular media,[19] but a poor assumption for fibrous mats. Equation 1 may be improved by substituting *(fiber-fiber clearance)* for d_{media}, since *(fiber-fiber clearance)* is a function of both mat porosity and fiber coarseness. Equation 1 in either form suggests that the probability of contact increases as fiber diameter decreases, for constant mat density or porosity.

If the density of the particle differs from that of the suspending fluid, and the particle is sufficiently large, particles can collide with fibers because inertia causes the particles to cross fluid streamlines. Inertia is related to a dimensionless group, the Stokes number, as defined in Equation 2:[19]

$$St=\frac{(\rho_p-\rho_l)d_p^2u}{18\varepsilon\mu d_f} \qquad \text{(Equation 2)}$$

where ρ_p and ρ_l = density of the particles and the liquid, respectively, d_p and d_f = diameters of the particles and the fibers, respectively, ε = porosity of the fiber mat, μ = fluid superficial viscosity, and u = fluid velocity. Schulze[22] has suggested that when the Stokes number is less than 0.1, the effects of inertia can be ignored, but when it is greater than 1.0, contact is virtually assured if the particle is within the fiber's flow column. This means that for virtually all particles smaller than about 10 μm, the effect of inertia may be ignored.

Suspended solids particles experience random movements relative to the fluid streamline due to temporary imbalances in the statistical number of collisions per unit area on the particle surface. This Brownian movement results in increased probability of contact with the fibers. The diffusion coefficient, D, associated with the Brownian movement is defined according to Equation 3:[19]

$$D=\frac{kT_{abs}}{3\pi\mu d_p} \qquad \text{(Equation 3)}$$

where T_{abs} = absolute temperature, and k = Boltzmann's constant. Most investigators have considered diffusion to be insignificant for particles larger than 1 μm,[18,19] while diffusion has been shown to characterize the retention of 0.1 μm TiO_2 particles quite well.[14-15,23-24] For larger particles, the importance of diffusion has been calculated by Herzig, et al.,[18] according to Equation 4:

$$\frac{x}{d_f}=\left[\frac{2D}{u(1/\varepsilon)d_f}\right]^{0.5}=\left[\frac{2T_{abs}\varepsilon k}{3\pi\mu d_p u d_f}\right]^{0.5} \qquad \text{(Equation 4)}$$

where x = square root of the mean square path (RMS diffusion path). If x is large relative to d_f, diffusion is thought to be significant.

Particles can also cross fluid flow streamlines due to sedimentation if their density differs sufficiently from that of the suspending fluid, and if their diameter is relatively large. The significance of sedimentation in increasing the probability of collisions between particles and fibers is determined by the ratio of the Stokes sedimentation velocity to the velocity in the

pore, combined to form a sedimentation coefficient, S, as defined in Equation 5:[19]

$$S = \frac{(\rho_p - \rho_l)\varepsilon d_p^2 g}{18\mu u} \qquad \text{(Equation 5)}$$

where g = acceleration due to gravity. Herzig, et al.[18] suggest that sedimentation plays some role in the probability of contact when the value of S is greater than 0.1.

Particles can also cross fluid streamlines due to hydrodynamic forces, which are related to local velocity changes as the pore dimensions change. Johnson[25] proposed a modified Reynolds number to characterize the hydrodynamic action for fluid passing through fiber mats, which follows the observed and anticipated trends. Johnson's modified Reynolds number is defined according to Equation 6:

$$Re' = \frac{u d_f \rho_l}{\varepsilon\mu} \qquad \text{(Equation 6)}$$

Note that Equation 6 is referenced to Johnson's dissertation,[25] because the journal publication version[14] contains an error in this equation.

Tiller[26] summarized the general forms of numerous investigator's modified Reynolds numbers for porous and fibrous media, and concluded that flow through deep bed filters is almost always laminar, except when the media is very large in diameter. Hence, hydrodynamic action is seldom considered to be significant for percolation situations, but in general is significant, for stirred systems.

It is generally assumed that fiber surface capture is directly proportional to both the probability of particle-fiber collision, and the magnitude of the surface attractive forces.

Particle Retention Forces

Forces which have been cited as significant for retention of small particles in deep bed filtration include axial pressure from fluid flow, friction forces, surface attachment forces, and chemical forces.[18] Chemical forces, caused by chemical reactions between the particles and the media, are generally ignored for paper industry suspended solids washing applications, because paper industry applications typically involve non-reactive systems, within a time frame relevant to suspended solids retention or washing.

Axial Fluid Forces

Axial fluid forces act on a particle when it encounters a constriction that it cannot enter. In some cases, the particle could move from the point of capture, for example under the influence of gravity, if the flow rate was drastically reduced, but increasing the flow rate should generally not free up particles captured by axial fluid pressure.

Friction Force

A particle can be captured in a constricted area if it or the fibers become slightly deformed under the pressure of the fluid force. In such cases, there is almost no chance that the particle will move, no matter what the flow rate, unless the flow is reversed, and is of sufficient magnitude.

Both axial fluid forces and friction forces involve sieving mechanisms, and could occur within the fiber mat, or at the surface of the mat. Sieving mechanisms are mechanical and are generally insensitive to superficial velocity.

Surface Attachment Forces

Most literature sources conclude that the forces of surface attachment in both filtration and retention can be accounted for by van der Waals forces, and electrokinetic forces.[18-19,27] Van der Waals forces are a combination of molecular-level attractive forces of permanent dipole moment orientation, temporary dipole induction, and dispersion effects, along with the repulsive force between the nuclei and electron clouds of neighboring molecules. The van der Waals net force, F, is sometimes expressed as shown in Equation 7.[28]

$$F = \frac{A}{r^7} - \frac{B}{r^n} \qquad \text{(Equation 7)}$$

where B is a constant for a given substance, A contains terms for polarizability, temperature, dipole moment, and various constants, r is the separation distance, and n is between 10 and 13. In principle, Equation 7 shows that the attractive forces are proportional to the inverse of the seventh power of the separation distance between the particles, while repulsive forces are proportional to the inverse of a higher power of the separation distance. This means that the attractive forces act over a very small distance, but the repulsive forces act over a much shorter distance.

The magnitude of the net intermolecular attractive forces can be put in perspective by comparing the bond energies and distances of the various chemical bonds, in Table 2. Van der Waals forces are very weak compared to primary valence bonds, or even to hydrogen bonds, yet they still require very

close contact.[26] The contact area of a small spherical particle bonded on a flat surface is small, compared to the surface area of the particle, so the particle could be dislodged if drag forces caused by fluid flow were sufficiently high. Hence, surface attraction forces are dominant only for very small particles, typically much less than 1 μm diameter, which have a relatively small surface area exposed to the fluid drag forces.

Table 2: Bond energies and distances for various interactions.[28]

Interaction	Bond energy (kcal/mole)	Bond distance (μm x 10^4)
Primary valence bond	50-200+	1-2
Hydrogen bond	4-10	2-3
Intermolecular attraction	0.5-5	3-5

For larger particles, in the macroscopic size range, the attractive forces decrease over a much greater distance, typically with the inverse of the square of distance. Experimental data from filtration trials tends to follow the trends shown in Equation 8, according to Herzig, et.al.[18]

$$\eta = \frac{\mu^{0.5}}{d_m^2 u} \qquad \text{(Equation 8)}$$

where η = retention efficiency, and d_m = media characteristic diameter.

Electrokinetic forces, also called ionic double layer forces, are also surface attraction forces. In electrolyte solutions, particles and media tend to adsorb ions of one type preferentially, especially if they have some ionizable groups on their surfaces, such as carboxylic acid groups on cellulose. A layer rich in ions charged opposite to the adsorbed layer forms around the adsorbed layer. The electrokinetic potential at the boundary of the double layer and the bulk liquid determines the electrokinetic interactions of the particle surface. Electrokinetic forces are attractive between opposite-charged, and repulsive between like-charged particles or media.

The electrical double layer may be compressed significantly, or the charge may even be reversed, by addition of ions, particularly multivalent ions. Charge reversal is usually the result of nonspecific adsorption of more charge than originally on the surface. It occurs more commonly with multivalent ions, and with pH changes. This means that the attractiveness of particles for the media, or for each other can be dramatically altered by changes in the ionic strength, or the pH.[19]

Zeta potential is a measure of the effective potential exhibited by a particle at the interface between the tightly bound adsorbed ions, and the more loosely bound counter-ions in the outer shell. It is often measured via micro electrophoresis and is used today in the paper industry as an indication of the strength of attraction between particles, or particles and fibers, for paper machine retention studies.[19]

The interaction between van der Waals forces and electrokinetic forces has been characterized by Akers and Ward[19] with potential energy diagrams similar to those shown in Figures 3 and 4. Curve 1 in Figures 3 and 4 shows the van der Waals forces, which are always negative, indicating attraction. Curve 2 in Figures 3 and 4 shows the repulsive effect seen by particles with like charges; this effect is always positive (repulsive) but can be relatively large or small, and is also a function of separation distance. Curve 3 shows the net force, which is mostly positive in Figure 3 indicating that the particles are repulsed from the fibers, and is always negative for Figure 4, indicating that the particles are attracted to the media, if they happen to become close enough together.

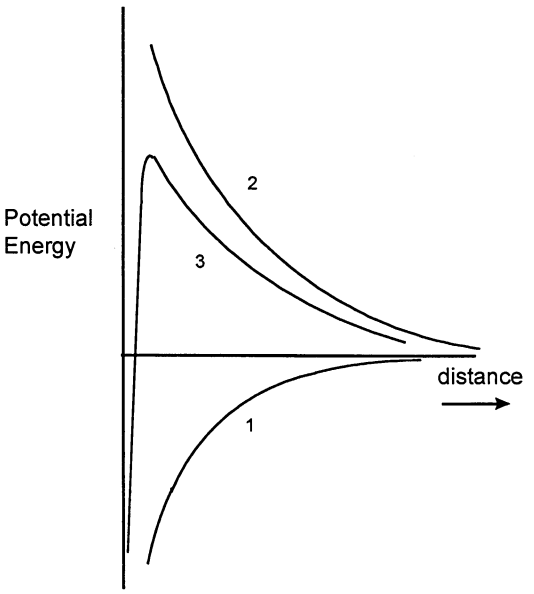

Figure 3: Potential energy diagrams for a non-coagulating system (after Akers and Ward[19]).

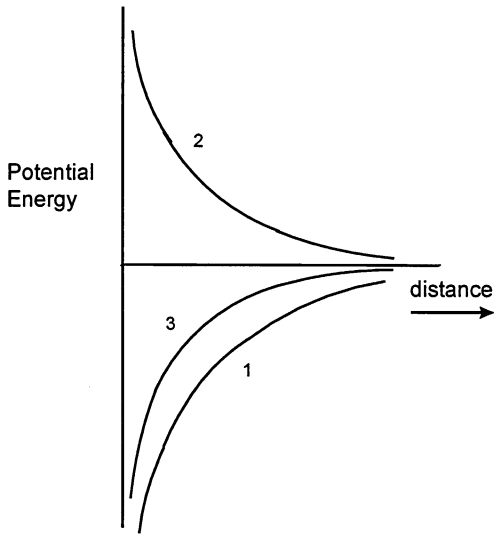

Figure 4: Potential energy diagrams for a coagulating system (after Akers and Ward[19]).

In addition, particles larger than 0.1 μm can have a secondary minimum in their potential energy curve, which allows for a weak attraction at distances much greater than those discussed above. These weak bonds would be particularly sensitive to increases in fluid drag caused by velocity changes.

Determining the Controlling Mechanism of Particle Retention

Paper industry investigators have long known that retention of filler size particles (about 0.1-0.2 μm) is controlled by surface chemistry, not by sieving. This point is illustrated very clearly in a brief article by Alince and Lepoutre,[17] which begins by demonstrating the effect of pH on the electrophoretic mobility of pulp fines, and 0.2 μm diameter latex and clay particles, as shown in Figure 5. The pH must be extremely low before the acidic H^+ of the fiber fines' carboxylic acid groups are mostly returned. By comparison, the clay and latex particles are negative (attractive to fibers or fines) at low pH, but become positive (non-attractive to fibers and fines) at about pH 4.7 and 7.6, respectively.

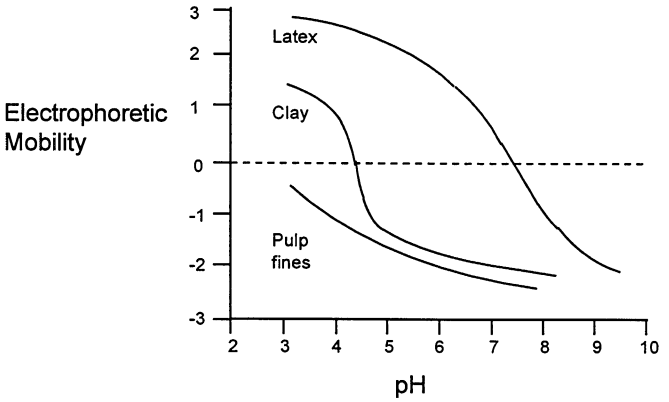

Figure 5: Electrophoretic mobility of 0.2 μm latex and clay particles, and fiber fines, as a function of pH (after Alince and Lepoutre).

Alince and Lepoutre showed that particles are retained very effectively at low pH, but practically not at all at high pH, in a percolated system, as shown in Figure 6; the same results were observed for a stirred system. This shows that particle capture must be based on fiber surface capture, due to surface attraction forces, in this case, since sieving could not be significant in a stirred system.[17]

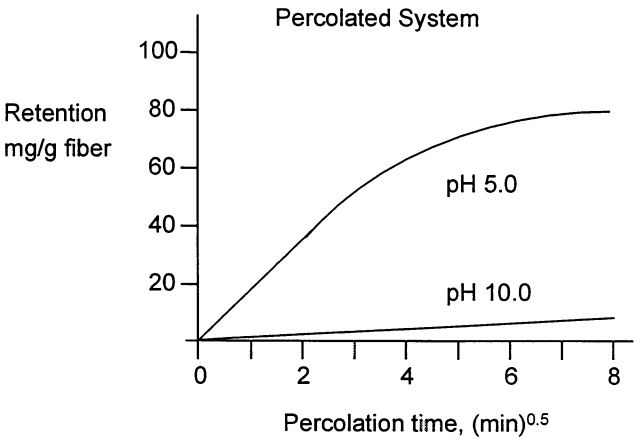

Figure 6: Retention of 0.2 μm diameter latex particles percolated through a pulp mat at high and low pH (after Alince and Lepoutre[17]).

Sieving can also be distinguished from fiber surface capture by observing the particle retention trends in percolation runs at different mat densities. Retention via sieving should increase as mat density increases. Retention via fiber surface capture should be independent of mat density, as long as the mean velocity through the inter-fiber spaces is maintained constant by adjusting the superficial velocity through the mat, assuming that the Reynolds number is still low.

When conditions dictate that sieving can be ignored as a particle capture mechanism, the mechanism by which particles contact the fiber surfaces for fiber surface retention can be determined by varying parameters which have different effects on the mechanisms of particle-fiber contact. The data is then fitted to the characteristic model for each particle-fiber contact mechanism, to determine which model best explains the results. For example, Johnson[14] determined that sieving was not the controlling mechanism for a TiO_2/nylon fiber system, by varying the superficial velocity. Sieving cannot be dependent on velocity, but his system showed such a dependence. He further determined that flow line interception was not controlling, because collection efficiency should be drastically improved as fiber diameter decreases, at constant Reynolds number, while in his system, fiber diameter did not influence the collection efficiency. Inertia was likewise ruled out, because collection efficiency should increase with superficial velocity, when in fact it decreased. Only diffusion control was consistent with all of the observed trends, for these very small particles.

Influence of Fiber Length on Particle Retention

The literature has rightly ignored the question of the effect of fiber length on particle retention. The area of the fiber ends, as a percentage of the total surface area of the fiber, is negligible at any reasonable fiber length. This suggests that particle capture on the fiber ends via surface attraction forces is insignificant compared to capture along the length of the fiber. Likewise, for internal sieving capture, if particle capture is primarily dependent on fiber-fiber clearance, fiber length assumed to be unimportant.

WASHING CHEMISTRY

The previous discussion assumes that no special washing chemistry, and no retention aids are present. Retention aids tend to enhance the capture of a wide range of particle sizes by greatly increasing the surface attraction forces between particles and fibers, even under relatively high shear conditions. By comparison, the goal of washing chemistry is to reduce the attractive forces between particles and fibers.

Washing chemistry has been compared to laundering.[29] The basic principle is to lift soil (ink, oil, dirt, etc.) which is usually oily and hydrophobic, from the fiber surface, keep it isolated from the fiber surfaces (to prevent redeposition), and keep it from combining with other particles (coagulation, agglomeration, collection, etc.). Properly isolated particles are dispersed, so that they behave independently of other particles and fibers, and are free to follow the flux of water through the fiber mat. The particle isolation effect is mostly accomplished via surfactants.

Surfactants are molecules with hydrophobic and hydrophilic groups. They form associations with their hydrophobic groups in the center of a sphere, and their hydrophilic groups facing outwards, called micelles. Micelles form only when the surfactant molecules are present in sufficient concentration; that point is called the critical micelle concentration, or CMC. Critical micelle concentrations differ substantially based on surfactant composition.[30-31]

The particle dispersion function of a surfactant is accomplished by forming micelles around the particles, such that the hydrophobic groups interact with the oily dirt particle surface, while the hydrophilic groups interact with the solvent (water). At that point, the micelle resists interactions with other particles and surfaces.[30-31]

Micelles are often depicted as shown in Figure 7; in proper scale, the surfactant molecules are several orders of magnitude smaller than the particles. As such, the diameter difference between the original oily dirt particle and the micelle is insignificant.[31]

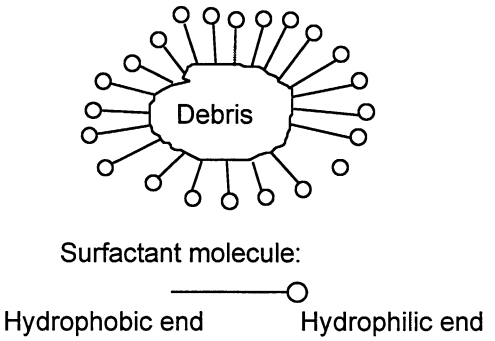

Figure 7: Popular depiction of a surfactant micelle. Length scale of the surfactant molecule is grossly exaggerated to show surfactant molecule orientation.

A given surfactant performs its detergency function best at a temperature 15-25 °C above its cloud point, which is the point where the surfactant molecules begin to form associations, clouding the solution. The temperature of maximum detergency is usually very close to the phase inversion temperature (PIT), where it inverts from an oil-in-water emulsion to a water-in-oil emulsion.[30]

Surfactant effectiveness is also dependent on its hydrophilic-lipophilic balance (HLB), which is the weight ratio of their hydrophilic to lipophilic groups. The HLB is often controlled by varying the ratio of ethylene oxide, a hydrophile, to

propylene oxide, a hydrophobe, in an EO/PO copolymer, in popularly used surfactant systems.[29,31]

Not surprisingly, the effectiveness of surfactants varies by soil (ink, dirt, etc.) type. This means that it is possible to design or select an optimum surfactant system for a specific type of ink or dirt, if the ink or dirt composition is well known. However, since most inks today contain a mixture of oils, and a given bale of recovered paper may contain a variety of inks, fillers, coatings, etc., optimization of surfactant chemistry under practical circumstances usually involves the use of surfactant blends, and significant on-site trials.[29]

SUSPENDED SOLIDS WASHING TECHNOLOGY

The historical view of suspended solids washing is that particles smaller than about 10 μm will follow the water split during washing, while progressively larger particles will be removed at progressively lower fractions of the water split. This tendency is shown in the now-classic illustration first proposed by Horacek in 1979,[32] and widely reproduced since then, for removal of offset ink particles with screw presses. A version of this illustration, shown in Figure 8, plots washer discharge consistency against washer efficiency factor, which is the ratio of actual to theoretical washing efficiency. Washer efficiency factor could also be defined as the ratio of the percent of suspended solids removed, to the percent of water removed.

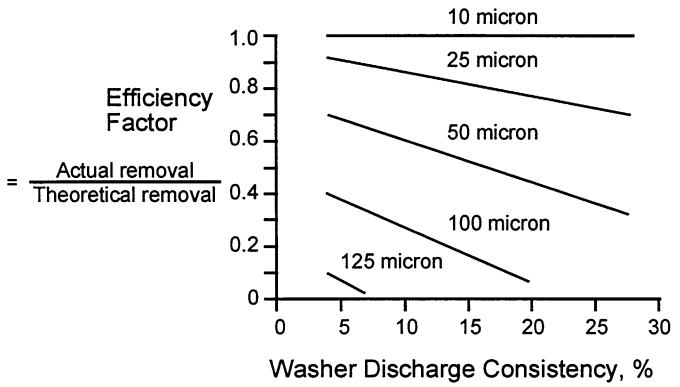

Figure 8: Ink removal efficiency factor vs. washer discharge consistency for various ink particle diameters (after Horacek[32]).

Overall suspended solids removal efficiency for a washing unit or system can be defined as shown in Equation 9 (theoretical) and Equation 10 (actual). The efficiency factor, ηF, plotted in Figure 8, can be defined by Equation 11.

$$\eta_T = \frac{(Water\,Removed)}{(Water\,Fed)} \qquad \text{(Equation 9)}$$

$$\eta_A = \frac{(SS\,Removed)}{(SS\,Fed)} \qquad \text{(Equation 10)}$$

$$\eta_F = \frac{\eta_A}{\eta_T} = \frac{(Actual\,Removal)}{(Theoretical\,Removal)}(100\%) \qquad \text{(Equation 11)}$$

The quantity of suspended solids per unit of fibers or per unit of liquid volume fed and removed can be conveniently expressed as mass:mass, area:mass, or area:area ratio. The same numerical result is obtained for ηA and ηT as long as the units for the numerator and the denominator in Equation 10 are the same, and as long as the size range of the particles under discussion is narrow.

It should be noted that a high value of ηF does not ensure good removal of suspended solids. Even when ηF approaches 1.0, ηT may still be low (i.e., a low hydraulic split), and hence, ηA is also low.

Other literature sources suggest that the basis weight of the pulp mat formed,[3] mat density,[33] or turbulence during washing[34-35] are responsible for deviations between theoretical and actual washing efficiency. To date, no mechanistic washing study results have been published.

The absence of a consensus opinion in the literature as to the dominant mechanism, and limiting conditions of suspended solids washing is understandable given the wide variety of hardware commonly used for suspended solids washing. Table 3 lists the theoretical washing efficiencies, maximum basis weight, a characterization of the relative shear level at the mat (expressed as relative velocity parallel to the mat face), and a characterization of the dewatering time and the cyclical nature of the dewatering force, if any. The values of these parameters vary by a factor of 10-20 from one device to another.[1-3,7,34,36-41]

Table 3: Characteristics of commonly used thickeners and suspended solids washers. All values are based on stock at 500-700 mL CSF.

Washer type	η_T, Theoretical efficiency	Maximum basis weight (g/m^2)	Dewatering Force (cm H_2O)	Average superficial velocity (cm/s)	Mat relative surface velocity (m/s)	Dewatering force cycle frequency (sec^{-1})
Decker	0.55-0.91	150-250	Gravity; <50, variable	0.3- 1.1 variable	<1.0	0.3 1 cycle
Vacuum disc filter	0.85-0.95	400-800	Dropleg vacuum; <500, constant	0.1-0.5 variable	0.2-0.4	0.03 1 cycle
High speed belt washer	76-98	60-100	Centrifugal force; <200, variable	2.3-10.5 variable	12-17*	10-50 1 cycle
Screw thickener	67-87	700-7000	Gravity, screw; ? variable	0.35-0.65 variable	1.0	N. A.
Fourdrinier forming section	95-98	20-400	Gravity, vacuum, centrifugal; 10-100, variable	0.5-3.5 variable (pulsed)	7-20*	40-90 20-40 cycles
Handsheet mold	99.8	60-200	Suction; 50-80, constant	3.5-7.0 variable	0	0.2 1 cycle
Modified pressure screen	66-94	?	Pump pressure; -50 to +150; variable	2.0-5.0 variable (pulsed)	20-25	25-50 65-130 cycles
Sidehill	54-91	50-150	Gravity; ≈0.5-1.5; constant	0.4-0.8 variable	N. A.; varies along unit	0.2-0.7 1 cycle
Low speed belt press	86-97	500-1000	Gravity, press rolls; ?, variable	very low variable	0.3-1.0*	0.5-1.0 4-5 cycles
Screw press	87-94	1500-5000	Screw pressure; ?, variable	0.2-2.0 variable	1	N. A.

* indicates that the fiber mat is not in contact with a stationary slurry, and that the fiber mat moves at the same velocity as the drainage media.

The values listed for η_T in Table 3 are based on normal minimum to maximum feed and washed stock consistencies. Maximum basis weight is based on exit conditions. Average superficial velocity is based on flow normal to the pulp mat, and averaged over the entire dewatering cycle. Instantaneous superficial velocity may be much higher early in the cycle, and much lower later in the cycle, in some cases. Mat relative surface velocity is the difference between mat velocity and slurry velocity, as an indication of the relative level of hydraulic shear at the mat:slurry interface. Dewatering force cycle frequency, and number of cycles applied to a unit volume of stock, are also indications of the shear environment; a high cycle frequency, and a large number of cycles suggest higher turbulence levels.

The importance of mat integrity can be clearly seen by comparing the turbulence level, hydraulic split range, and washing effectiveness of commercial washers. Figure 9 ranks the major classes of commercial washers by turbulence level, hydraulic split range, and inlet/outlet consistency.[34] The range of solids losses for the various types of washers, as listed in Table 4, can be compared with these characteristics.

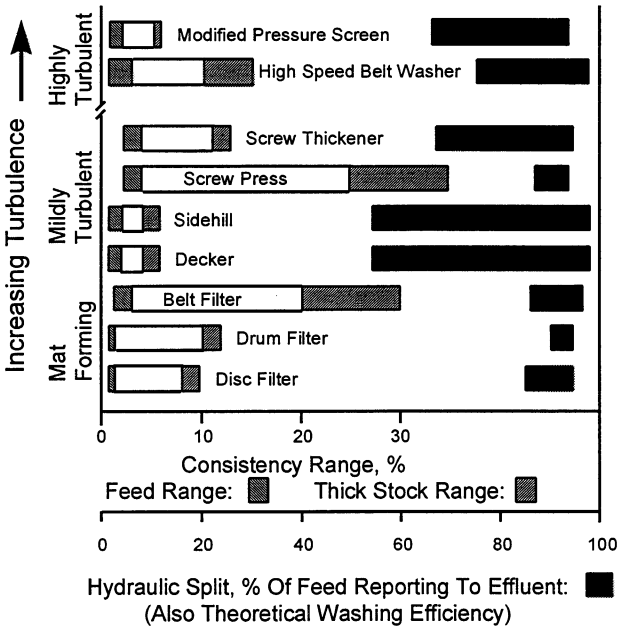

Figure 9: Characteristics of commonly used commercial washing devices

Table 4: Typical suspended solids loss range of commonly used commercial washers on 70% news/30% magazine furnish.

Washer type	Solids loss range (% of feed)
Mat Forming: (Disc, drum, and belt filters)	1-5
Mildly Turbulent: (Deckers, sidehill screens, screw presses, and screw thickeners)	10-25
Highly Turbulent: (High speed belt washers, and modified pressure screens)	25-45

As shown in Figure 9 and Table 4, the low shear, mat-forming washers have a very high hydraulic split range, and a very low suspended solids loss range. This suggests that they are not effective for removal of suspended solids, although the suspended solids removed are generally free of fiber. Low speed mat forming washers are better thickeners and dissolved solids washers than suspended solids washers.

By comparison, the mildly turbulent washers are characterized by a wide hydraulic split range (except for the screw press), less mat integrity, and higher suspended solids losses. They are better suspended solids washers, but the larger screen plate openings typically found in these devices, and the higher level of turbulence (poor mat integrity) also allow considerably higher amounts of fiber to be lost.

The highly turbulent washers operate in a very high shear environment, and mat integrity is almost nil. They are excellent suspended solids washers, but they also allow the highest suspended solids losses. As with most of the other washers, the loss of useable fiber is highly dependent on the operating conditions and the media opening size.

Even for a given type of washer, increasing the shear level has been shown to increase the value of η_F. This tendency is shown by Bliss, et.al.,[34] for a high speed belt washer, by varying its operating speed, even though the mat is disrupted only at the conclusion of the washing cycle. Comparable trends are reported when the shear level of a mat-forming device (a decker) is increased via addition of a variable-speed rotor in the vat,[34] and by the addition of spray nozzles, which also disrupt the mat.[42]

CONCLUSIONS

Suspended solids washing can be compared to retention, and deep bed filtration, since the same mechanisms of particle retention (media surface capture, and sieving) are important in both cases. Major differences also exist; when retention of very small particles is important, the surface chemistry conditions must be adjusted to maximize surface attraction forces between the particles and the media. Capture of larger particles, by sieving, is best accomplished by operating in a percolation mode, since media bed disruption could release previously captured larger particles.

In paper industry applications, effective removal of suspended solids requires appropriate adjustment of chemistry, to suppress the surface attraction forces, and to allow the particles to remain free of each other, so that they are free to migrate among the fibers. While high levels of turbulence during washing generally result in better removal of larger particles, there is a corresponding increase in the loss of useable fiber solids. Operating conditions must be chosen carefully to allow sufficient removal of suspended solids with minimal loss of useful fiber solids.

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